Cross-Borehole Electromagnetic Induction for Reservoir Characterization

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Summary

Audio-frequency cross-borehole electromagnetics (EM) is an interesting alternative to existing techniques for reservoir characterization. With this method signals may be propagated several hundreds of meters through typical sand/shale reservoirs and data may be collected at high accuracy with a high sensitivity to the subsurface resistivity. A vertical component, cross-borehole EM field system has been designed and built by Lawrence Livermore and Lawrence Berkeley laboratories for reservoir evaluation and monitoring. This system was deployed at the British Petroleum test facility in Devine, Texas for testing. The site is in a region of simple, flatlying geology so that collected data could be unambiguously interpreted with layered models. The results of the test showed that crosshole EM profiles in wells spaced 100 meters apart data could be repeated in 24 hours to better than one percent and that the profile data could be fit to layered models within this same tolerance.The derived models showed a close correspondence with the borehole induction log.

Introduction

The electrical resistivity of most sedimentary rock is a function of pore fluid type, its saturation and the porosity of the rock. For these reasons borehole resistivity logs have long been used by reservoir geologists and engineers to distinguish between rock types, map variations in pore fluid and to determine completion intervals in wells.

There is an obvious need to extend our knowledge of the electrical resistivity distribution from the immediate vicinity of the borehole, as is the case in induction logs, to the region between boreholes. Although this may be accomplished using a variety of surface and borehole configurations we have found that the greatest sensitivity is achieved when measurements are made between boreholes. This is simply because the data are collected closer to the region of interest.

Recent cross-borehole electrical/ electromagnetic research has concentrated at opposite ends of the frequency spectrum. Daily et al. (1990) and Shima (1990) have reported success using cross-borehole dc resistivity. Previous applications of the high frequency electromagnetic method (HFEM) to the cross-borehole problem have yielded mixed results. In high resistivity rocks (hard rocks or rocks with low salinity pore fluids) applications of HFEM have provided high resolution tomographic images of gas fire-fronts and fractures in coal seams (Davis et. al., 1979, Lytle et. al., 1974). In regions of lower resistivity (soft sedimentary rocks or rocks with high salinity pore fluids) HFEM results have been disappointing due to severe attenuation of source waves by the medium. Experimental results for enhanced oil recovery operations (EOR) reported by Harben and Pihlman (1988) at the Texaco Kern river site showed that 20 Mhz HFEM signals did not propagate more than a few meters through the sand/shale host rock before attenuation to undetectable levels.

An interesting alternative to HFEM is the EM induction method. This method differs from HFEM chiefly by operating at audio rather than radio frequencies (0.25 - 20 Khz vs 2-200 Mhz). At these lower frequencies the energy propagation is diffusive rather than wave-like.

The EM induction method offers several significant advantages over HFEM in through-the-earth imaging applications. 1) At audio frequencies the signals may be detected at much greater distances than HFEM. In typical sand/shale petroleum reservoir rocks it is practical to make high accuracy cross-borehole measurements from wells spaced up to 400 meters apart. 2) The induction measurements are simpler to make and interpret. External interference and "sneak path" wave propagation are major problems at high frequency but they are relatively insignificant at these lower frequencies. 3) A final advantage is that the data may be unambiguously interpreted in terms of resistivity or changes in resistivity of the rock through which the signal has passed. With HFEM it is often difficult to separate resistivity from permittivity effects.

Lawrence Livermore Laboratory (LLNL) and Lawrence Berkeley Laboratory (LBL) jointly began addressing the problem of collecting and interpreting audio-frequency cross-borehole EM data in 1989. In this program we have developed a field system, written numerical codes to interpret data and have deployed our system in a field environment where the geology is simple and well known. In this short paper we will describe our system and show some results from the field test.

Cross-borehole EM System

The LLNL/LBL cross-borehole EM system is a vertical component induction system designed for cross-hole imaging. The transmitter section consists of a custom-designed vertical coil driven by a commercially available EM transmitter. The coil is 8cm in diameter and 4m long weighing approximately 100 kg. At an operating current of 6 amps it has a dipole moment (product of the current, the number of turns and effective cross-sectional area) of more than 1000. This is sufficient signal for propagation through conductive rocks for up to 400m. Signals are detected in a second borehole with a vertical-axis custom-designed receiver coil. This is an ultrasensitive device, operable in the frequency range from 100-100,000 Hz, and designed for depths up to 2 km. Detected signals are amplified within the coil then transmitted to the surface up the logging cable. At the surface they are further amplified and filtered before input to a lock-in detector at the receiver van. Two electrically isolated hard-wire links between the transmitter and receiver are used for phase reference and position (depth) logging. The isolation is critical as it prevents the high level signals at the transmitter from contaminating the low level signals at the receiver. In the van all instruments are controlled by a desktop computer via the GPIB interface. The computer can adjust instrument gains and sensitivities as well as select sample and averaging rates for the logging system.

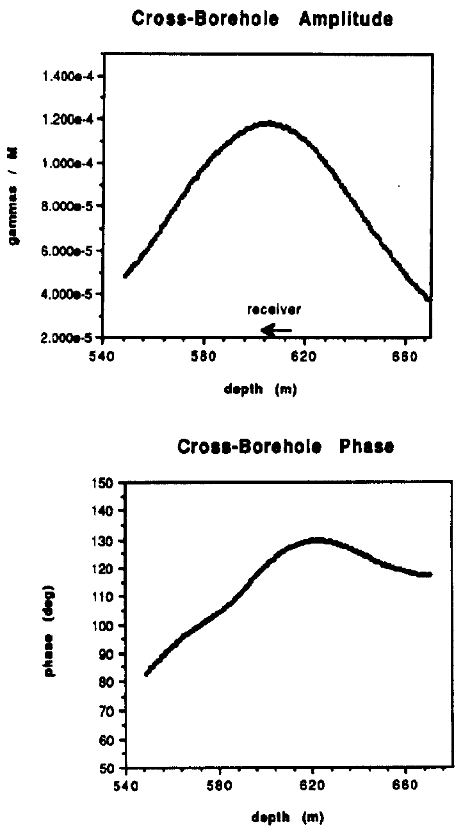

Figure 1 Sample cross-borehole amplitude and phase measurements. The receiver is located, as shown, and the transmitter,is in a separate borehole 100 meters away.

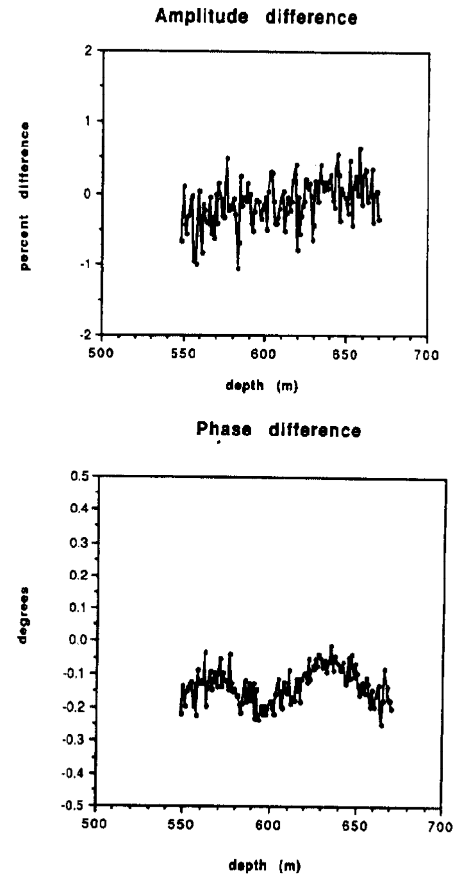

Figure 2 Percent difference amplitude and phase difference in degrees for a repeat of the above profile taken 24 hours later.

A particular borehole segment is logged by moving the transmitter coil at a fixed rate while the receiver remains stationary. Measurements are made while the transmitter coil is moving at a rate of 3-5 m /minute. This allows sufficient time for signal averaging but it is still a reasonable rate for data collection.

Sample cross-borehole magnetic field plots are given in Figure 1. These results are taken from the Devine test site experiment explained in the following section. The plots show the amplitude and phase of the vertical magnetic field at 512 Hz as the transmitter moves between 550m and 670m in one borehole while the receiver is fixed at 598m in a second borehole 100m away. The amplitude plot shows a smoothly varying magnetic field that forms a peak where the source and receiver coils are in closest proximity and an approximately symmetrical decrease in field strength away from the peak. The transmitter moment is approximately 1000 so the detected fields are at the level of tens of picoteslas.The phase data are also smooth but they display more character than the amplitude results. Near 600m the phase forms a peak and it "rolls off" sharply above this depth which correlates to a decrease in subsurface resistivity.

The above profile was measured twice on successive days to establish the precision level of the system; the difference between the data sets is displayed in Figure 2. This Figure shows that the amplitude difference over the 24 hour period was less than 1.0 percent for all points with an average of 0.3 percent. The difference in phase averaged less than 0.2 degree. Both of these are well within the guidelines of 1.0 percent for amplitude variations and 0.5 degrees for phase established for imaging requirements (Zhou,1989).

In many ways the borehole environment is a benign one for EM measurements. At depths more than a few hundred meters the influence of cultural electromagnetic noise and vibration is greatly diminished. The often variable and troublesome surface layer does not affect interpretation since measurements are made at depths considerably beneath it.

Field Test: British Petroleum Test Site Devine, Texas

The Devine test site, established and operated by British Petroleum is located some 30 miles southwest of San Antonio, Texas. The site was established to test geophysical methods and instrumentation. It is located in an isolated area, away from sources of cultural noise, but still within reasonable access to population centers. Three wells are available for experimental use; two of the wells are steel-cased to 160m and plastic lined below this to a depth of 900m. The geology at the site consists of a sequence of sandstones, shales and limestones. Individual beds are continuous and flatlying across the entire site as is evident from an examination of the well logs. The borehole resistivity logs show variations from 1 to 300 ohm-meters with the higher resistivity layers (limestones) concentrated towards the base of the section and the sandstone and shale layers ranging in resistivity from 1 to 10 ohm-m (see Figure 4).

For the Devine test we chose to collect a set of cross-hole profiles spanning a change in resistivity from 2-3 ohm-meter sands and shales to 30 meter thick 10 ohm-m predominantly limestone strata and back to sands and shales (see Figure 4). For each profile the source moves between fixed depths 120m apart and the receiver remains fixed in the other borehole at a depth within these limits. Subsequent profiles are then made between the same source positions using different receiver locations. Each set of profiles corresponds to 13 receiver position covering a similar depth span as the source coil.

The cross-borehole amplitude and phase data for the above profiles are shown as contour plots in Figure 3. The amplitude data dominantly reflect the relative positions of the source and receiver coils, peaking where the coils are in closest proximity. The peak amplitudes are larger at the lower parts of the section which corresponds to a zone of higher resistivity, (and lower field attenuation).In contrast, the phase data are rich in character showing a smooth, continuous variation of more than 120 degrees within the profile span. The maximum phase values generally correspond to the high resistivity limestone, the minimum phases correspond to the lower resistivity sands and shales. The contact between these layers, located at a depth of 600m, can be correlated with sharp gradients in the phase data.

A further test of our system is to match the field data to layered models. In areas where the rocks are flatlying a layered resistivity model should be electrically equivalent to the resistivity well log. Fortunately at the Devine site the resistivity logs indicate that the strata are continuous and flatlying and therefore this site should be well suited for a layered model interpretation.

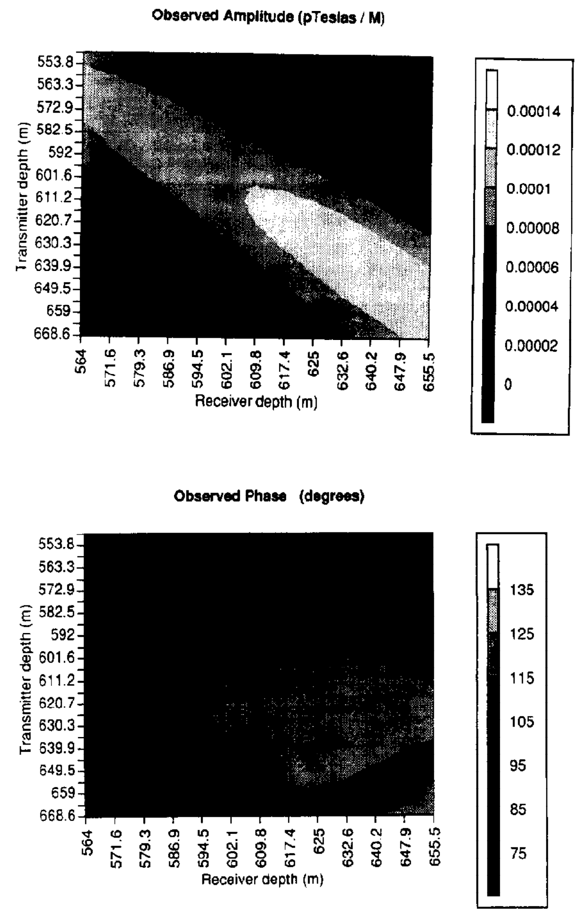

Figure 3 Contoured cross-borehole amplitude and phase data for the Devine survey.

We selected the above field profiles and fit the phase data, profile by profile, using computer program **NLSEM1D** developed at Lawrence Berkeley Laboratory. The program does a layered model inversion, of up to 20 distinct layers, using arbitrary cross-borehole or surface-to-borehole magnetic field data. Only every fifth point in the cross-borehole profile is used in an effort to save computer time. First-guess layer boundaries and resistivities were assigned to match within about 20 percent with the induction resistivity log. The program was then free to adjust resistivities and layer boundaries until a fit was achieved.

In Figure 4 we show a comparison of the layered model inversion for the profile from receiver station 609.8 to the borehole induction log spanning the same depth interval. The data were fit at an average of 0.2 degrees which is typical of the inversion results and similar to the repeatability errors shown in Figure 2. The correspondence between the layered model inversion and the induction log in Figure 4 is remarkably similar which bodes well for using this technique for field characterization.

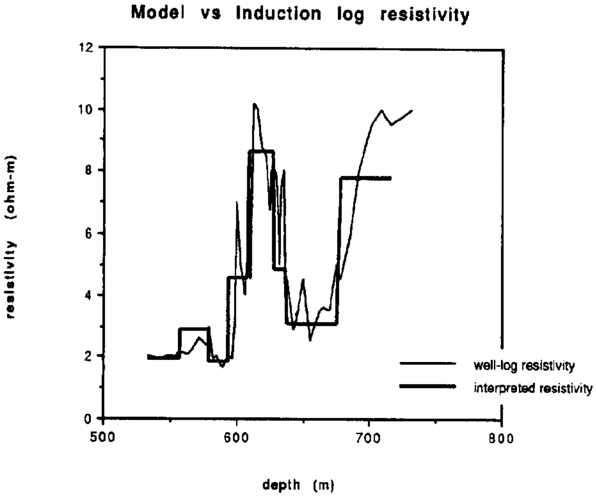

Figure 4 Comparison of interpreted cross-borehole EM data and the borehole induction log in the same interval.

Acknowledgement

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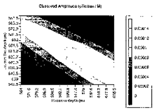

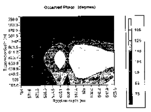
Observed Phase (degrees)